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Global Innovation Systems – A conceptual framework for innovation dynamics in transnational contexts

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Abstract

This paper proposes a framework for the analysis of technological innovation processes in transnational contexts. By drawing on existing innovation system concepts and recent elaborations on the globalization of innovation, we develop a multi-scalar conceptualization of innovation systems. Two key mechanisms are introduced and elaborated: the generation of resources in multi-locational subsystems and the establishment of structural couplings among them in a global innovation system (GIS). Based on this conceptualization, we introduce a typology of innovation modes in four GIS configurations, building on the knowledge base and valuation system in different industry types. The analytical framework is illustrated with insights from four emerging clean-tech industries. We state that a comprehensive GIS perspective is instrumental for developing a more explanatory stance in the innovation system literature and developing policy interventions that reflect the increasing spatial complexity in the innovation process.

Keywords: innovation system; globalization; clean-tech industry; industry typology; innovation policy

1. Introduction

In a globalizing knowledge economy, the mobility and circulation of people, knowledge, and capital increasingly interrelates innovation processes in distant places (Corpataux et al., 2009). The increased spatial complexity of innovation processes raises the question whether a territorial (local, regional, or national) *system* perspective is still a valid one as system boundaries get increasingly blurred and porous. More fundamentally, some argue that the innovation system (IS) perspective, on a more general level, is no longer a promising line of research and should be left on the shelves of the history of innovation studies, as concluded in a plenary debate at the 2013 DRUID conference.[1]

In the present paper, we argue against this view and maintain that a systemic perspective still holds considerable explanatory potential, not the least when adapted to increasingly internationalized innovation processes. However, to realize this potential, a number of conceptual improvements are required. The strong focus on actor networks and institutions that condition innovation in regional and national systems needs to be combined with greater emphasis on the role of multi-scalar networks and systematic differences between the innovation processes in various industries. This calls for a more integrative view in which various innovation system perspectives and related literatures on the globalization of innovation stop living parallel lives and start talking to each other in more engaged and reciprocal ways (Martin, 2016; Weber and Truffer, 2017).

To elaborate on this proposition, we take a closer look at the challenge of international interdependencies in the innovation process. Over the last decade, authors have argued that the spatial configuration of innovation systems is getting more complex, spanning actor networks and institutional contexts from various places and across spatial scales (Bunnell and Coe, 2001; Carlsson and Stankiewicz, 1991; Coe and Bunnell, 2003). While various analytical approaches have started to conceptualize the increasing importance of international linkages between regional and national innovation systems (for an overview see e.g. Carlsson, 2006; Grillitsch and Trippl, 2013), a comprehensive and operable analytical framework for global innovation systems is still missing. In particular, existing concepts were criticized for remaining rather vague in their conceptualization of interdependencies between various territorial subsystems at an international level (Binz et al., 2014; Coenen et al., 2012; Grillitsch and Trippl, 2013; Wieczorek et al., 2015a).

The present paper aims to address this challenge by reinterpreting the overlaps between various innovation system approaches. In particular, we aim at specifying how key system resources for innovation get created and integrated at a global level. In this venture we build on existing multi-scalar perspectives on innovation from various IS traditions, but elaborate two new conceptual dimensions. First, we define subsystems of a GIS not based on pre-defined territorial boundaries, but based on the actor networks and institutions that are involved in creating specific system resources (knowledge, market access, financial investment and technology legitimacy (see Binz et al., 2016b)). Whether or not the actor networks and institutions in each of these dimensions fall within territorial boundaries, is treated as an empirical question. Second, we argue that the performance of a system in developing and diffusing innovation depends not only on the existence of coherent subsystems, but also on the availability of structural couplings between them. Structural coupling is attained if specific actors, actor networks or institutions span across or overlap between various subsystems, be this in a specific region or country, in a global non-governmental organization or a transnational corporation.

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[1] Available at https://vimeo.com/155650827

Second, we draw on recent insights from the sectorial systems literature to explain differences in the spatial configuration of GIS in various industry types. Our framework differentiates between an industry's dominant innovation mode - STI (science-technology and innovation) vs. DUI (doing, using and interacting) (Jensen et al., 2007) - and the economic system of valuation in which markets for the innovation are constructed - standardized products for global mass markets vs. customized products depending on symbolic valuation in local contexts (Huenteler et al., 2016a; Jeannerat and Kebir, 2016). Based on empirical illustrations from recently emerging clean-tech sectors, we discuss how the spatial configuration of GIS differ between industries that produce standardized commodities with an STI innovation mode (i.e. consumer electronics, solar photovoltaic modules) and industries with a DUI innovation mode that depend on a valuation process that is customized to specific territorial contexts (i.e. luxury watchmaking, wind power). This heuristic creates new hypotheses on why in some industries national and regional innovation system boundaries remain relevant, while in others territorial boundaries are increasingly transcended by international interdependencies. Policy interventions that target specific national or regional subsystems will accordingly lead to different spatial spillovers depending on the overall GIS configuration.

These arguments will be elaborated as follows. We first review existing IS literature relative to the role of international linkages. Section 3 integrates these insights to a novel concept of global innovation systems, focusing on subsystems and their structural couplings. Section 4 develops a taxonomy of GIS configurations in different industry types and illustrates them based on recent case studies from the wind power, solar power, carbon capture and storage, and electric car industries. Section 5 discusses methodological challenges and outlines a broader research agenda in the field of global innovation systems. We conclude with policy implications and the framework's contributions to research at the interface of economic geography and innovation studies.

2. Existing perspectives on innovation systems in transnational contexts

2.1 Earlier attempts to conceptualize global innovation systems

Innovation system studies emphasize that innovation emerges from complex interactions between actors with complementary (technological, managerial, investment or regulatory) competencies, which operate under specific institutional settings (Lundvall, 1992). The use of a system metaphor emphasizes the distributed, yet more or less coordinated agency that underpins the innovation process; interaction between firms, universities, policy makers and various intermediaries creates positive externalities that are of key importance in the innovation process, but very difficult to be produced or controlled by any actor on its own (Nelson, 1993).

Over the years, different variants of IS have been formulated and applied empirically, including a national (Lundvall, 1988), regional (Cooke et al., 1997), sectoral (Malerba, 2002) and technological (Carlsson and Stankiewicz, 1991) approach. Superficially, the distinguishing feature of each framework lies in the way system boundaries are set, i.e. in determining which elements contribute to the generation of innovation-related positive externalities and which ones do not (Bergek et al., 2015). Yet, when comparing the approaches more deeply, one finds significant differences in each tradition's epistemology, research objectives, and methodological approach (Coenen and Díaz López, 2010). Given these differences, various streams of IS research have lived largely parallel lives, without much cross-fertilization between their research networks (Coenen and Díaz López, 2010). The existing literature on 'global', 'international' or 'multi-scalar' IS (Anadon et al., 2016; Archibugi and Michie, 1997; Binz et al., 2014; Bunnell and Coe, 2001; Carlsson, 2006; Dewald and Fromhold-Eisebith, 2015; Niosi and Bellon, 1994; Oinas and Malecki, 2002; Pietrobelli and Rabellotti, 2009; Sagar and Holdren, 2002; Spencer, 2003) generally reflects this lack of interaction between varying research traditions.

First and foremost, NIS and RIS scholars departed from a territorial perspective in emphasizing the importance of institutionally embedded face-to-face interaction in the innovation process (Lundvall, 1992). Capability accumulation, interactive learning and capacity building in national and regional contexts became the key focus of research. When conceptualizing the globalization of innovation, NIS and RIS scholars started from the customary assumption that regional/national contexts matter most for innovation and then moved to explain the links between territorially embedded innovation processes (for a comprehensive overview see Carlsson, 2006). Another illustrative example is the work by Oinas and Malecki (2002), who provide a comprehensive conceptual approach on how innovation processes in various RIS complement each other in a global division of labor.

This approach later got criticized for providing a rather static concept of innovation and employing 'spatial fetishism' (Moulaert and Sekia, 2003). By a priori setting national or regional borders as scalar envelopes, NIS and RIS concepts could not fully capture the activities of organizations, networks and institutions evolving at a supranational level and understanding how they influence territorially embedded innovation dynamics (Coenen et al., 2012). GIS concepts in the NIS and RIS tradition thus mostly show that territorial subsystems still matter, even though they get increasingly interconnected at supranational levels. Yet, there is no shared understanding on how these interconnections emerge, how they matter, let alone whether they matter for all industries and markets in the same way (Coenen et al., 2012).

Scholars in the SIS tradition complemented the NIS and RIS concepts by arguing that industry- and technology-related rather than country-related or regional factors mostly affect the (spatial) organization of innovation (Breschi et al., 2000; Malerba, 2005; Spencer, 2003). Comparative empirical work in a broad range of sectors (such as semi-conductors, cars, pharmaceuticals, telecommunications, machine tools, etc.) consistently showed similarities between innovation processes of the same sector in different regions (Jung and Lee, 2010; Malerba, 2005; Malerba and Nelson, 2011; Yu et al., 2016). SIS scholars developed elaborate sector taxonomies, which were grounded in the technological regimes and trajectories that structure the innovation process (Castellacci, 2008). This approach allowed developing rigorous analytical frameworks, which however also attracted strong criticism for their technology bias. In particular, SIS studies increasingly downplayed the importance of more distributed forms of agency, non-firm actors and the influence of informal institutions on the innovation processes (Coenen and Díaz López, 2010). Also, given the concept's roots in evolutionary economics and its reliance on standardized quantitative databases (e.g. NACE codes), it tended to focus on long-term industrial dynamics in existing manufacturing sectors (Castellacci, 2008), while lacking explanations for the emergence of new sectors and technologies (Coenen and Díaz López, 2010).

This latter critique was taken up by TIS scholars who focused their empirical work almost exclusively on the dynamics of system building and industry formation in emerging (clean-tech) sectors. To cover these complex dynamics, the analytical focus was extended beyond system elements and structure to core processes (or 'functions') as a means to assess system performance (Bergek et al., 2008; Hekkert et al., 2007). Seven key system processes were identified from an extensive literature review and an inductive aggregation of empirical studies, including knowledge production and diffusion, entrepreneurial experimentation, resource mobilization, guidance of the search, market formation, creation of legitimacy, and the creation of positive externalities (Bergek et al., 2008; Hekkert et al., 2007). Since, various empirical applications have validated and refined this analytical framework (Markard et al., 2015). Yet, most empirical work in the TIS tradition also set a priori system boundaries at a national level and restricted the analysis to cleantech industries, arguing that this was a coherent set of industries with similar technological trajectories. So, even though the TIS framework offers explicit concept of system dynamics and in principle embraces an international perspective, it recently also attracted criticism for spatial fetishism in its empirical application and a neglect of differences in the innovation process between sectorial contexts (Bergek et al., 2015; Binz et al., 2014; Coenen et al., 2012).

Summarizing this short discussion, existing attempts to internationalize the innovation system concept did not take advantage of the ample complementarities that exist between different IS perspectives. In our view, three key improvements are needed in a more integrative GIS perspective. First, it should conceptualize the key system elements and the contexts in which positive externalities (or system functions) emerge from a spatially open, multi-scalar perspective. The key question for IS research is not whether the embedding of innovation processes in national or regional territorial contexts still matter, but how it matters and whether it matters differently for different types of technologies and industries. Secondly, the perspective should be dynamic and able to explain the processes that lead to the creation (and decline) of new technologies and industries. Third and finally, it should account for systematic differences between innovation dynamics in various industry types. In the remainder we will address these issues by first reassessing the basic conceptual notions of the IS literature (actors, networks and institutions) and introducing a process-based evaluation of resource formation at a (global) system level. Second, inspiration is drawn from the work on the internationalization of NIS and RIS to conceptualize the complex spatial interplay of circulation and anchoring of innovation-related system resources in territorial and non-territorial contexts. Finally, we rely on recent advances in the SIS literature to define a typology that distinguishes between GIS configurations in four generic industry types.

2.2 Re-thinking the structure and key processes of global innovation systems

The core structural element of innovation systems are the actors engaged in the development and diffusion of new technologies, the formal and informal networks they form as well as the institutional contexts that regulate these interactions (Bergek et al., 2008; Lundvall, 1992; Malerba, 2002). Actors include firms, research organizations, government departments, NGOs and other intermediary organizations that contribute to the development and diffusion of innovation. In IS approaches, actors have been conceptualized as internally homogenous entities with clearly defined interests and pursuing coherent strategies with respect to the innovation-related objectives (Morrison et al., 2008). When extending the analysis to international contexts, actors have to be conceptualized not as atomistic agents per se, but as a “constitutive part of the wider network through which emergent power and effects are realized over space” (Hess and Yeung, 2006: 1196). This point applies most directly to multinational companies, but is equally relevant for other actor groups such as research and education organizations, professional and industrial associations, (international) non-governmental organizations, citizens’ movements or even regulatory bodies with global reach (Boli and Thomas, 1997; Gosens et al., 2015; Meyer et al., 1997).

The conceptualization of actor networks has to be reconsidered accordingly. The seemingly obvious distinction between networks at the regional, national and international scale becomes increasingly blurred (Coe and Bunnell, 2003; Crevoisier and Jeannerat, 2009). Firms may coordinate activities in various intra-organizational or extra-organizational networks and along a continuum of governance forms ranging from market exchange, to network forms of inter-firm governance, to full integration and direct ownership (Gereffi et al., 2005; Musiolik et al., 2012). International networks are a materialization of different geographic and non-geographic proximities that can be institutionalized to different degrees ranging from the full integration in a formal organizational context (hierarchy) to loosely coupled virtual and epistemic communities as in the field of software development (computer games, Wikipedia). They can be long-living and continuous such as international professional associations or topical and ephemeral such as conferences of epistemic of practice-based communities (Maskell et al., 2006).

Also formal and informal institutions may have varying spatial reach (Drori et al., 2003; Fuenfschilling and Binz, 2017; Meyer et al., 1997). Among the often-cited regulatory institutions in IS research are international policy regimes and treaties (Conca et al., 2006), as well as technology transfer mechanisms (for instance the clean development mechanism of the Kyoto protocol), that set boundary conditions for innovation processes (Gosens et al., 2015; Lema and Lema, 2016). Intellectual property rights (IPRs) are a specific form of an internationally valid institution that is crucial to the functioning of many innovation activities (Auerswald and Stefanotti, 2012). But also cognitive and normative institutions can develop validity beyond specific territorial contexts in the form of technological paradigms, professional cultures, or dominant rationalities of world culture (Boli and Thomas, 1997; Drori et al., 2014; Strang and Meyer, 1993).

Overall, in an internationalized perspective, innovation systems are constituted by multi-scalar actor networks and institutional contexts that jointly support (or hinder) the formation and diffusion of novelty. In some cases, they may be reducible to specific territorial contexts, yet in others, they depend on actor strategies, networks and institutional dynamics that co-evolve between different parts of the world. The combination of actors, networks and institutions that support or hinder innovation in GIS are thus almost countless and alternative configurations of the system structure can lead to similar performance characteristics (Bergek et al., 2008; Edquist, 1997). As the different system elements become more complexly structured at an international level, integrating the key system functions from TIS literature seems promising. It allows structuring the externalities that support industry formation and innovation into four generic types of system resources – knowledge, market access, financial investment and technology legitimacy - which may each evolve in their own spatial configuration (Binz et al., 2016b). In this perspective, global innovation systems consist of sub-systems which create these four types of system resources and which are linked by multi-scalar actor networks and institutional contexts. This spatially open understanding of IS comes near to the core ambition of global innovation networks formulated by Ernst (2002), namely to assess “how the combinations of concentrated dispersion with systemic integration determines the emergence of new opportunities for transnational knowledge diffusion and adoption”. Yet, the GIS approach goes beyond this view by encompassing non-knowledge based activities like market formation, investment mobilization or the creation of technology legitimacy.

3. Layered structures and processes in Global Innovation Systems

Two new conceptual elements thus have to be elaborated in more detail: 1) subsystems[2] of a GIS in which system resources form and 2) structural couplings between subsystems. In the following, we will elaborate these elements and then propose a heuristic for assessing their spatial configuration.

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[2] The RIS approach also draws on the notion of sub-systems (Asheim and Gertler, 2005) through a distinction between knowledge exploration and knowledge-exploitation. In our paper we extend this basic idea by incorporating additional dimensions like investment mobilization, market formation and technology legitimation.

3.1 Subsystems and structural couplings

In NIS and RIS studies, positive externalities were assumed to emerge more or less uniformly within a national or regional territory. Also work on international or global innovation systems argued that regional or national levels remain the key scales for externality formation, but added an international interaction layer. In a GIS perspective, this seems oversimplified. Giuliani and Bell (2005) and Giuliani (2007) used the global wine industry as a case to show that knowledge resources in RIS are available in highly selective and uneven ways, also at the regional level. When adopting an internationalized view and considering not only knowledge-based resources, this asymmetry gets further intensified.

The question of "where" system resources form and which actors can access them therefore moves center stage. We define subsystems not in a spatially pre-defined way, but as the actor networks and institutional contexts involved in the formation of system resources (Binz et al., 2014; Coenen et al., 2012). Subsystem boundaries can correspond to national or regional borders, but they may as well develop in networks that transcend national and regional borders. An example of a subsystem developing in a multi-scalar network would be legitimacy for an agricultural produce that stems from a fair trade label, which is constructed between globally active NGOs, a transnational company, and farmer's collectives in developing countries. Other examples of relational externality formation processes are those created by dispersed communities of practice like in the open source software field. Here, actors are often not spatially collocated, but still develop shared cultures, knowledge stocks and investment models that are hard to copy and access for outsiders (Lakhani and Von Hippel, 2003). A similar example is knowledge on membrane bioreactor technology, which initially emerged from a global innovation network spanning engineers in French transnational water companies and research institutes in various places around the world (Binz et al., 2014).

As innovation ultimately depends on how actors combine knowledge, investment, markets and legitimacy to new configurations that work, the overall development of a GIS will depend on whether and how the resource formation processes in the four subsystems are coupled to each other. Such 'structural coupling' relates to the foundational elements of an IS - actors, networks and institutions (see Bergek et al., 2015). Examples of coupling domains could be an internationally active firm that is able to connect knowledge resources from a regional innovation system to market segments in distant places. An example of institutional couplings is given by professional cultures (e.g. of engineers or technology consultants), which enable the formulation of globally shared technology standards and by this enable economies of scale to be reaped in different markets (Sengers and Raven, 2015). Network coupling might happen at international conferences and trade fairs, where information from different subsystems of the GIS get exchanged and recombined (Maskell et al., 2006).

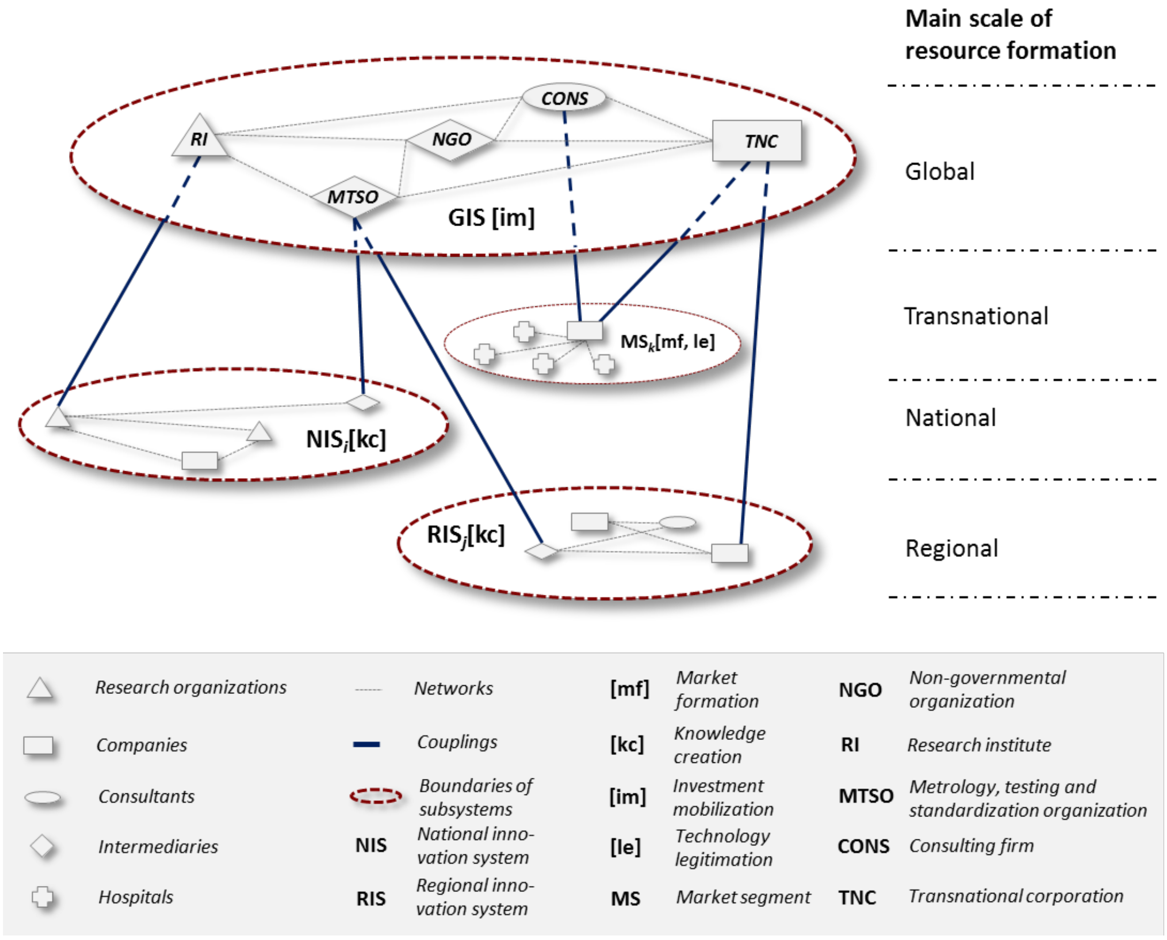
In GIS, resource formation and structural coupling are accordingly multi-polar, fluid and subject to intensive contestation. As key system resources are emerging from subsystems with varying geographies, actors in the GIS will in many cases not be able to directly appropriate a dominant share of them in-house or inside a given region or country. They will rather have to create strategic alliances and rely on non-geographic types of proximities to access and anchor a full resource portfolio in a given place (Binz et al., 2016b; Boschma, 2005). Concentrations of innovative activity develop in hubs where the actors involved in different subsystems meet and interact (Binz et al., 2014). In some cases, these hubs may be territorially confined, in other cases they may develop temporarily at international conferences and trade fairs (Bathelt et al., 2004), or emerge from the international networks of TNCs or global NGOs (Dicken, 2015). Resourceful actors with a global reach (such as TNCs, global donor organizations or professional and industry associations) are in a structurally superior position to facilitate effective hubs, but they might as well emerge in a specific region with very dense personal and inter-organizational networks, or even from a loosely coupled community of traveling technology experts (Larner and Laurie, 2010).

3.2 A multi-scalar representation of GIS

Resource formation in subsystems may accordingly give rise to a host of multi-scalar system topologies, especially compared to the geographically rather flat representation of system structure in the NIS and RIS tradition. Figure 1 provides an illustrative mapping of a hypothetical GIS structure in the public health domain. On a first layer, actors with global reach (a TNC, as well as a consortium of research institutes, standardization bodies, consultancies and international NGO's) interact to ascertain the mobilization of financial investment (GIS [im]). An example could be an initiative by the Bill and Melinda Gates foundation, which provides funding for R&D on a cure for AIDS. A second subsystem is constituted around the process of knowledge creation, which happens in specialized (biotechnology) research institutes and start-ups in a specific NIS (NIS_i[kc]). Structural couplings are established by international research programs and the integration of the national standard setting bodies into the technology standardization committees of the World Health Organization. A related knowledge subsystem emerges from a regional technology cluster which provides a supportive institutional environment for specialized technology development (e.g. for advanced vaccination technology, (RIS_j[kc])). Structural couplings are facilitated by a branch plant of a TNC located in the RIS that actively contributes financial investment and knowledge to the local innovative milieu. The fourth subsystem is provided in a new market segments (MS_k[mf]) which is established by a TNC and a consulting company in well-renowned university hospitals in selected cities around the world. In this subsystem, learning about market needs and user response take place and the initial legitimacy for the product is established (MS_k[le]).

Success of the GIS will now not only depend on the quality of the resource formation processes in each subsystem, but on the ability of key actors to couple these dispersed activities into a coherent innovation trajectory at a global level. The global innovation system will perform well (here: develop a cure for AIDS) if different subsystems are well established and interconnected and thus able to mobilize and re-combine system resources for the development and diffusion of the innovation.

Figure 1: Generic structure of a hypothetical global innovation system in healthcare



Source: Author's own elaborations

4. Towards an industry-sensitive perspective on GIS evolution

So far, our elaborations mostly focused on how the GIS framework captures the tension between territorial embedded and spatially dispersed externality formation. Based on these elaborations, one can now ask whether any sort of GIS configuration is equally possible when a new technology emerges and matures or whether specific GIS structures are more likely to develop given certain technology and industry characteristics. For that purpose, the framework needs to be connected to recent insights from the SIS and industry lifecycle traditions (Dosi and Nelson, 2013; Huenteler et al., 2016a; Malerba and Nelson, 2011; Schmidt and Huenteler, 2016). We start from the basic tenet from SIS literature that differences in the properties of the knowledge base, technological opportunities, cumulativeness and appropriability conditions influence the technological paradigms of an industry, which in turn influences the spatial contexts in which innovation takes place (Malerba, 2005). Yet, the GIS framework complements this rather 'supply-side' driven explanation with a more structured view on the 'demand side' of innovation. To date, SIS research has not fully included user-producer interaction as a constitutive element of the innovation process (Coenen and Díaz López, 2010; Geels, 2004; Lundvall, 1988). As Jeannerat and Kebir (2016: 277) put it, SIS scholars have "analyzed in ever more complex ways the endogenous knowledge processes driving economic change in production, but have usually left aside the question of how this change is endogenously valued in and related to market construction”. We addresses this criticism by emphasizing the co-evolution of a technology and its institutional embedding not only for knowledge-based technological innovation, but also for three complementary subsystems that spur market formation, resource mobilization and technology legitimation. This basic idea can be condensed into two principal components that shape GIS dynamics in an (almost) orthogonal way: technological innovation and product valuation.

4.1 The technological innovation dimension

In the technological innovation dimension, the RIS, NIS and SIS traditions provide well-established arguments on the spatial configuration of knowledge production in different industry types. At a most aggregate level, one can distinguish industries dominated by a science and technology driven (STI) innovation mode from industries where innovation relies more strongly on learning by doing, using and interacting (DUI) (Jensen et al., 2007). The STI mode plays an important role in science-based industries with an analytical knowledge base (i.e. biotechnology, pharma, solar PV), while the DUI mode characterizes innovation in engineering-based industries with a synthetic knowledge base (car manufacturing, machine tools, wind power) (Asheim et al., 2007; Herstad et al., 2014; Martin and Moodysson, 2013). Innovation in STI-based industries depends on knowledge that develops from the application of scientific principles and which can get codified in models, patents and reports. Formalized R&D inside the company, tight industry-university linkages and repeated radical technology breakthroughs characterize these fields (Huenteler et al., 2016a). As knowledge is codifiable into patents, rules, blueprints etc., it can get disembodied to some degree - especially if compared to DUI-based knowledge (Jensen et al., 2007). Knowledge exchange in internationalized networks, e.g. in scientific communities or international professional networks, thus plays an important role in STI-based innovation processes (Asheim and Coenen, 2005; Martin and Moodysson, 2013). This industry type will accordingly depend on significant knowledge spillovers beyond regional and national borders (Moodysson and Jonsson, 2007; Schmidt and Huenteler, 2016), so the innovation-related subsystem of their GIS will develop in complex, multi-scalar networks that often transcend specific regions and countries.

In industries where the DUI-based innovation mode is more dominant (e.g. luxury watchmaking, specialized machine tools, wind power), in contrast, learning depends more strongly on novel recombination of experience-based knowledge and competencies (Huenteler et al., 2016a; Jensen et al., 2007; Martin and Moodysson, 2013). New knowledge is not predominantly developed through scientific abstraction, but rather through on-the-job training, as well as by interaction between various firm departments and outside actors. New combinations emerge not predominantly from formal R&D, but from solution-oriented producer-user interaction (Huenteler et al., 2016a; Jensen et al., 2007). In this more incremental way of learning, tacit knowledge embedded in craft and practical skills is of high importance (Asheim and Coenen, 2005). Innovation processes in a DUI-based GIS accordingly depend on spatially more ‘sticky’ externalities because spatial co-location and continuous face-to-face interaction facilitate tacit knowledge circulation (Martin and Moodysson, 2013; Schmidt and Huenteler, 2016). Innovation processes in GIS with a DUI-based innovation mode will thus be characterized by a knowledge subsystem which is more deeply rooted in specific region’s historically grown institutional contexts.

This first distinction is well aligned with existing conceptualizations in various IS traditions. It can also be related to recent work in industry lifecycle literature (Huenteler et al., 2016a; Schmidt and Huenteler, 2016), which argues that STI-based industries tend to follow a conventional Abbernathy-

Utterback (1978) industry lifecycle model, while DUI-based industries are more likely to develop the lifecycle model of complex products and systems as outlined by Davies (1997). It is also important to note that while some industries may be relatively clearly attributable to either pole, most industries will depend on some combination of DUI and STI-based elements, not the least if one decomposes the full value chain of an industry (Stephan et al., 2017). This important caveat will be discussed in more detail in section 4.3.

4.2 The product valuation dimension

The second dimension assembles industry characteristics that relate to the other three system resources; market access, financial investment and technology legitimacy. These characteristics are conceptualized as the key components of valuation processes, i.e. the processes by which a new technology becomes a valued product for a specific customer segment (Jeannerat and Kebir, 2016). This process is first of all dependent on mechanisms of 'market formation' in a narrow sense. New products in their early stages typically depend on protected market niches (often supported by government subsidies). They also need the formation of new use-patterns and preferences, the establishment of socially accepted price-performance relationships and reputational capital accumulated by suppliers in the form of brands and labels (Dewald and Truffer, 2011; Fligstein, 2007). In addition, broader processes of technology legitimation come into play before users may derive value of existing technologies and products (Johnson et al., 2006; Suchman, 1995). Products have to be aligned with pre-existing institutional structures in order to be accepted as valuable ways of consumption (Bork et al., 2015; Markard et al., 2016). An often-cited example are genetically modified organisms, which have shaped food markets in fundamentally different ways in Europe compared to the US (Murphy et al., 2006). Finally, also financial investment may be characterized as an important dimension of valuation, which has undergone increasing pressures for globalization (Yeung and Coe, 2015). In general, investment can be raised for the promise of future turnover generated by new products (Karltorp, 2016). In that sense, it is here understood as the anticipation of future market formation and legitimation processes.[3]

The different valuation processes play out differently in specific industries. In some cases, they lead to products that are very homogenous across different contexts. For instance, markets for consumer goods like detergent, shampoo or smartphones look similar all over the world. Knowledge and financial channels to support valuation are rather standardized and markets and technology legitimacy are well-established. However, in industries with more complex or radically novel products, the valuation process requires a broad range of proactive social construction processes that deal with (niche) market formation, attracting investment and legitimacy conditions (Binz et al., 2016a; Jeannerat and Kebir, 2016). In these cases, technological knowledge may result to be of less decisive importance for overall innovation success. In the extreme, we may think of industries where the management of valuation processes is overwhelmingly important while technological advances may almost be neglected - as in the case of luxury watch making or micro beer brewing (Jeannerat and Crevoisier, 2013). The stylized dichotomy of standardized and customized valuation can be translated

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[3] Note that financial resources are not only relevant for valuation processes. Firm-internal R&D investments or public spending for science and technology are key inputs at the innovation side, as well. Yet, it is here assumed that their mobilization depends on some form of (proto-)valuation processes. The effects of conventional R&D funding and science policies will be addressed policy implications section at the end of the paper.

into a gradient (the x-axis in Figure 2) that runs from industries with predominantly standardized products and distribution channels (consumer goods, mass-tourism, solar PV) towards industries where new products and markets are co-produced between suppliers and consumers in highly specific territorial contexts (construction, legal advice, biogas) (Abernathy and Utterback, 1978; Davies, 1997; Huenteler et al., 2016a; Jeannerat and Kebir, 2016).

In the case of 'standardized valuation', consumption and legitimacy are stabilized around clearly identified goods, services and brands. End-users have relatively undifferentiated preferences that are uniform in various parts of the world and base their acquisition choices mainly on price signals (Jeannerat and Kebir, 2016). Demand articulation, marketing, and sales are relayed through specialized market research and advertising organizations, and user demand can be served with standardized distribution channels (ibid.). Therefore, also financial investment operates on rather standardized assessment procedures established by investment banks or large companies. Once a mass market has formed, it constitutes a system resource to which actors from the whole GIS have access. They can supply it with products without much need for adaptation to specific regional contexts. Valuation processes in this industry type are accordingly relatively footloose; globally valid dominant designs and quality standards will homogenize valuation dynamics in various parts of the world.

In contrast, in industries that depend on 'customized valuation', products need to be tailored to the needs of specialized user groups or depend on symbolic embedding in historically grown territorial contexts (Jeannerat and Kebir, 2016). New market segments are constructed in a complex negotiation process in which users and producers attach specific symbolic meaning to a new technology or product (Dewald and Truffer, 2012). Design and branding get incrementally adapted to shifting user needs, changes in the wider institutional context, or new technological opportunities. Innovation, marketing and sales strategies accordingly rely on strategic institutional entrepreneurship aimed at aligning consumer's normative and cognitive associations with a specific innovation (Binz et al., 2016a; Jeannerat and Kebir, 2016; Wirth et al., 2013). Financial investors need to build on this highly place-specific knowledge in order to identify future winning products. We would therefore expect financial investment to be mobilized by local investors or firm-internal financial assets. Successful valuation in one specific region of the GIS does not automatically imply that its markets are easily accessible for actors in other places. To gain trust by specialized users, outsiders would have to invest heavily in getting embedded into local networks and institutional contexts. The valuation-related subsystems in this GIS type will accordingly rely on actor networks that remain spatially sticky and embedded in specific regional/national contexts over extended periods of time.

4.3 A typology of generic GIS configurations

The above considerations now allow us to construct a typology of four generic GIS configurations based on industries' innovation and valuation characteristics (see Table 1 and Figure 2). As many industries are characterized by complex combinations of DUI and STI-based learning as well as standardized and customized valuation, the use of Cartesian coordinates in Figure 2 does not imply that industries can be precisely positioned in the two dimensional graph with numerical values, but rather that they can be compared in this two-dimensional continuum relative to each other. Also, their position in the coordinate system is in most cases not stable, but subject to industry lifecycle dynamics (see section 4.4).

This notwithstanding, at any given point in time, industries can be positioned on a continuum (the y-axis in Figure 2) between being dominated by STI-based knowledge (e.g. biotechnology, semiconductors) or having a stronger reliance on DUI-based knowledge (e.g. machine tools, construction and trade) (see Jensen et al., 2007 for a detailed discusssion). The same holds true for the valuation dimension: Industries with highly standardized valuation systems (e.g. apparel, food retail) would be positioned close to the 'standardized' pole on the x-axis, while education or biogas represent industries that would be located close to the 'customized' pole. Some industries with very complex value chains such as car manufacturing, pharma, aerospace or business software programming depend on integrative mixes of DUI and STI-based learning as well as customized and standardized valuation. Analytically, we would either position them closer to the center of Figure 2 or decompose them into various value chain segments that are more easily attributable to one of the four ideal-type GIS configurations.

The – admittedly still rough – categorization in table 1 is valuable as it enables new hypotheses on how industry characteristics determine the (spatial) configuration of their underlying innovation systems (cf. section 4.4). The resulting differences have far-reaching consequences for the spatial spillovers we expect in the innovation process and related policy implications (cf. section 5.3). In addition, it helps in positioning existing global innovation system concepts in a broader GIS framework. We denominate GIS as 'spatially sticky' if both the innovation and the valuation subsystems depend on territorially embedded context conditions. Industries that are characterized by these conditions are akin to the spatial innovation systems proposed by Oinas and Malecki (2002) or Carlsson (2006), in which various regionally strongly embedded (national or regional) innovation systems get interlinked in a long-distance 'division of labor'. 'Production-anchored GIS' relate more closely to the typical innovation system configurations reported in the cluster or RIS literatures. They emphasize local buzz and global pipelines as key determinants of knowledge generation processes (Asheim and Isaksen, 2002; Bathelt et al., 2004), while assuming valuation processes will be rather footloose, so markets are typically rather internationalized and standardized. 'Market-anchored GIS' on the other hand relate to industries that are often analyzed in the sustainability transitions or the policy mobilities literatures. They emphasize that innovation happens in internationalized networks of firms, universities and professional associations, while valuation depends on highly localized embedding competences (Fuenfschilling and Binz, 2017; Saxenian, 2007; Sengers and Raven, 2015). Finally, GIS structures, which build on easily codifiable knowledge and result in standardized valuation, may be termed as 'footloose GIS'. They represent the most globalized industry configuration, which represents the majority of paradigmatic cases of the global value chain literature (Dicken, 2015; Gereffi et al., 2005).

Table 1: Four ideal-type global innovation system configurations

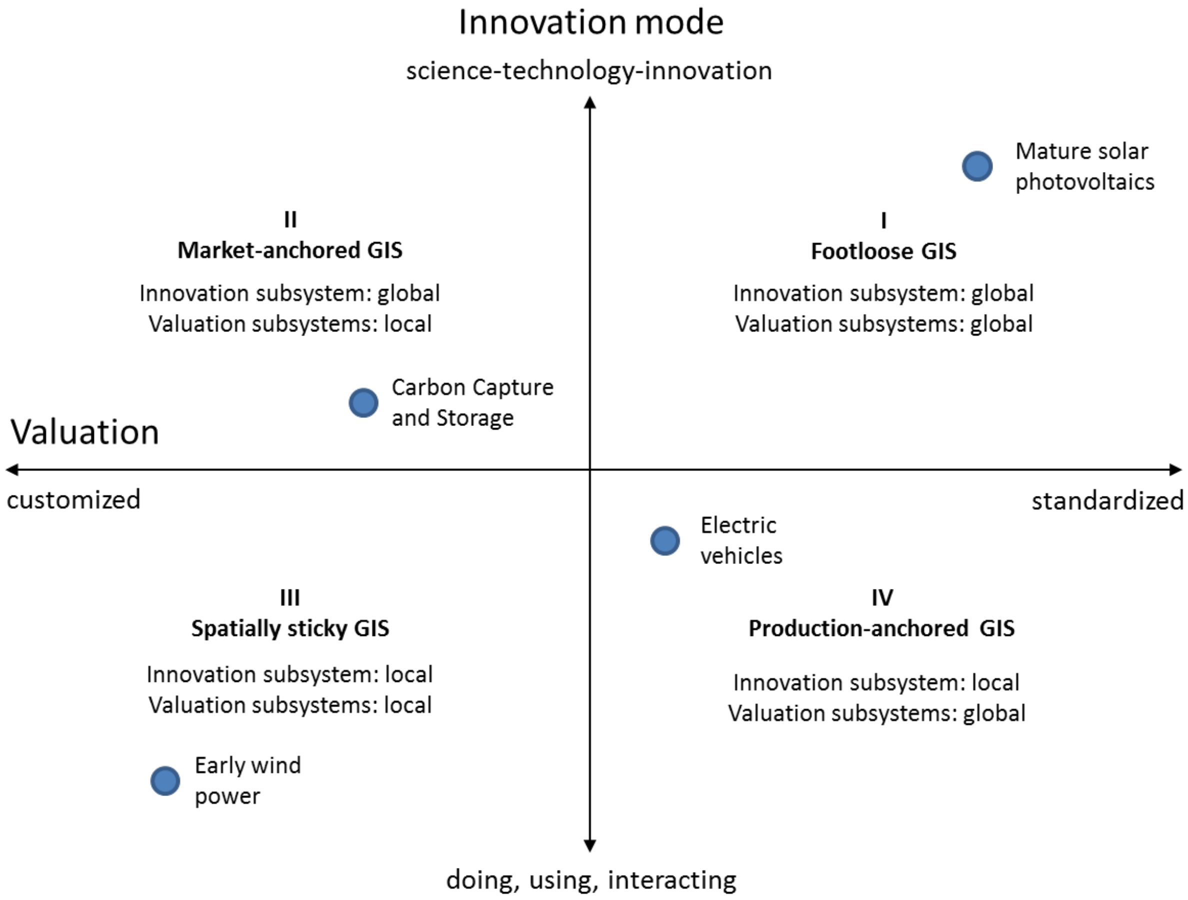
		Valuation	
		Customized	**Standardized**
Innovation	**STI mode**	**Market-anchored GIS** - *Knowledge*: Footloose. Spatial spillovers in international networks/communities - *Financial investment*: Rather footloose. Channeled through TNCs and large institutional investors - *Market formation*: Sticky. Adaptation of products to local contexts, creation of user preferences in local niche markets - *Legitimation*: Rather sticky. Strong dependence on pre-existing institutional contexts, scope for international standards *Structural couplings:* TNCs, academic networks, transnational demonstration projects, international associations and NGOs *Typical examples:* Carbon capture and storage, nuclear energy, water treatment, accounting & tax services, hospitals, insurance	**Footloose GIS** - *Knowledge*: Footloose. Strong spatial spillovers in international networks/communities - *Financial investment*: Footloose. Venture capital, investor-driven. Company listings at international stock exchanges - *Market formation*: Footloose. Mass markets with economies of scale, market-based price competition - *Legitimation*: Footloose. International standards and technology codes. Coherent user preferences in various institutional contexts *Structural couplings:* International trade in products and manufacturing equipment, patens/publications, international trade fairs, academic networks *Typical examples:* Solar photovoltaics, consumer electronics, pharma, bulk chemicals, software coding, investment banking & trading, call-centers
	DUI mode	**Spatially sticky GIS** - *Knowledge*: Sticky. Regional milieus with dense user-producer-intermediary interaction - *Financial investment*: Sticky. Focus on local funding sources, patient capital, seed funding from angel investors - *Market formation*: Sticky. One-of-a-type niche markets. 'Project' business models, customization to local conditions - *Legitimation*: Sticky. Embedding in (and adaptation of) local institutional contexts. *Structural couplings:* Long-established knowledge pipelines, mergers and acquisitions, mobility of technology experts *Typical examples:* Wind power, biogas, luxury watchmaking, construction, educational services, personal services (legal, financial, health, etc.)	**Production-anchored GIS** - *Knowledge*: Sticky. Regional manufacturing clusters with specialized knowledge providers - *Financial investment*: Rather sticky. Local institutional investors, family ties, focus on brand value and reputation - *Market formation*: Rather footloose. Regional cultural milieus from which symbolic meaning is mobilized for global markets - *Legitimation*: Footloose. Homogenization of user tastes through advertisement/marketing *Structural couplings:* TNCs, joint ventures, global marketing & sales organizations, industry associations, international professional communities *Typical examples:* Automobiles, apparel, furniture, private banking, business services, computer games, motion pictures, mass-tourism (resorts, cruises)

Source: Author's own elaboration

4.4 Empirical illustration: GIS configuration in four emerging cleantech industries

To further discuss the heuristic value of this framework we will now illustrate it with examples from the burgeoning literature on innovation systems in clean-tech sectors (cf. Figure 2). In the following, we will exemplify the development of GIS structures for the solar photovoltaic, wind power, carbon capture and storage (CCS) and electric car industries, each of which can be positioned in a different quadrant of Figure 2. The aim of this exercise is purely illustrative; a comprehensive test of the GIS framework's empirical validity will be left to future analyses.

Figure 2: Positioning of selected clean-tech industries in the innovation-valuation framework.



Source: Author's own elaboration

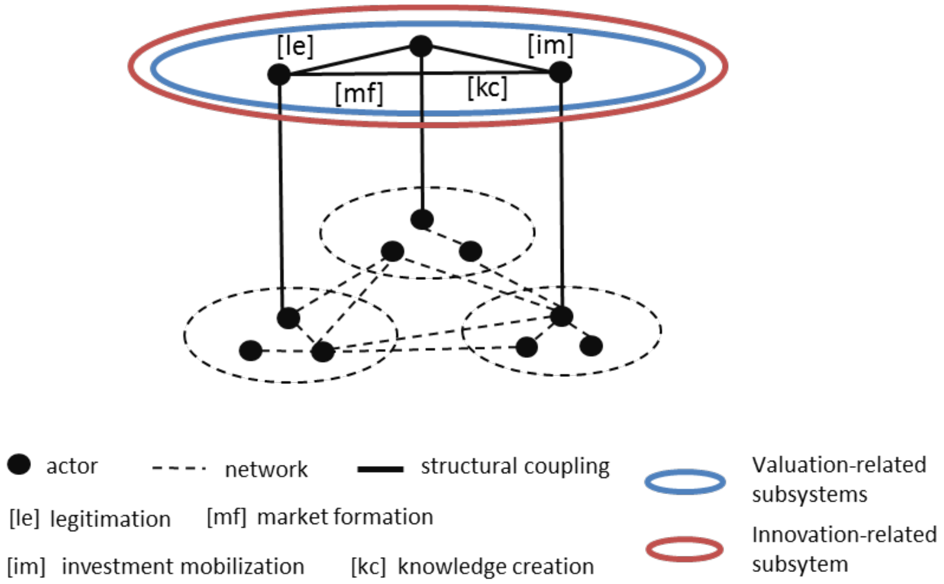
A) Footloose GIS: Solar photovoltaics (Quadrant I)

The top-right quadrant exemplifies the GIS of industries that are subject to the lowest possible level of territorial embeddedness: As the relevant knowledge bases, investment mechanisms, market conditions and quality specifications can be codified and standardized, international networks and trade will play a key role at both the technological innovation and valuation side (Figure 3).

An industry that nicely illustrates this GIS-type is solar photovoltaics (PV) (for an in-depth discussion see Huenteler et al., 2016a; Schmidt and Huenteler, 2016). Innovation in PV technology depends on advances in analytical knowledge bases like material sciences or nanotechnology (Huenteler et al., 2016a; Peters et al., 2012), while economic valuation is nowadays organized in standardized, global mass markets (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015). System resource formation accordingly depended on specific territorial subsystems only in the earliest life-cycle phases, e.g. when the pioneering companies in the USA and Japan created initial knowledge and technology legitimacy in 1970-1990 (Varadi, 2014), or when pioneering markets were constructed in Germany between 1990 and 2005 (Dewald and Truffer, 2012). Yet, once these system resources had been created in one place, technology latecomers - most prominently from China - could directly mobilize and anchor them in their own industry formation processes (Binz and Diaz Anadon, 2016; Huang et al., 2016; Quitzow, 2015). Nowadays, all subsystems in the PV field depend on complex networks spanning several regions in developed and emerging economies (Binz and Diaz Anadon, 2016; de la

Tour et al., 2011; Gallagher and Zhang, 2013; Quitzow, 2015) and it is hardly possible anymore to identify specific places or regions that dominate the innovation process in this industry (Binz et al., 2017). Structural couplings at an international level are ubiquitous. Emblematic examples comprise US and European investment banks that organized IPOs for Chinese PV module manufacturers in the mid-2000s (de la Tour et al., 2011; Zhang and White, 2016) or German suppliers of turnkey manufacturing lines that base their innovation activities on close interaction with Chinese manufacturing companies and universities in various continents (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015). Also in the valuation dimension, the PV industry only initially relied on policy support in specific national contexts. Today, the valuation subsystems are complexly coupled at an international level, i.e. with the World Bank and the international electrochemical commission (IEC) developing globally harmonized quality standards and testing procedures for solar PV modules that essentially harmonize market entry barriers in various parts of the world (Cabraal, 2004; Varadi, 2014).

Figure 3: GIS configuration in the solar photovoltaics industry



Source: Author's own elaborations

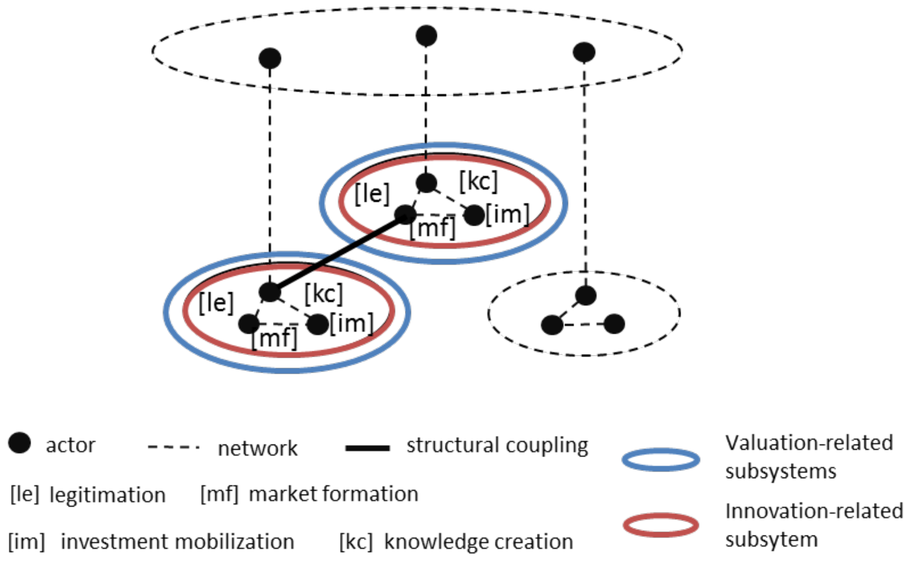
B) Spatially sticky GIS: wind power (Quadrant III)

The GIS configuration of the early wind power industry, starkly contrasts the case described above. Technological innovation in this industry depended heavily on subsystems and structural couplings in territorially delimited contexts (for a detailed discussion see Huenteler et al., 2016a; Lewis, 2011). Especially in the earlier industry lifecycle phases, innovation in the wind power GIS was dominated by complex 'bricolage' processes in which synthetic knowledge stocks got interrelated with experience-based skills and crafts (see Garud and Karnoe, 2003). Also at the valuation side, markets were not globally homogenous, but showed strong geographic variation in terms of specialized user needs, regulation, and levels of technology legitimacy.

In the early wind power industry, turbine manufacturers strongly drew on a DUI innovation mode (Garud and Karnoe, 2003; Huenteler et al., 2016a), while market deployment depended on institutional embedding and regional technology legitimation (Garud and Karnoe, 2003).[4] Empirical case studies consistently show that innovation in spatially clearly distinguishable subsystem - e.g. in the USA, the EU, and in particular Denmark – played a key role in steering the wind industry from a long era of ferment to a dominant product architecture (Karnøe and Garud, 2012; McDowall et al., 2013; Simmie et al., 2014; Wieczorek et al., 2015a). Territorially embedded learning by doing and interacting and co-located actor networks with complementary knowledge in manufacturing and application (turbine manufacturers, farmer's collectives, research and testing organizations, governmental intermediaries) initially constructed the relevant system resources in only two countries: Denmark and the US (Garud and Karnoe, 2003; Karnøe and Garud, 2012; Simmie, 2012). Later on, activities emerged also in Germany as well as India and China (Gosens and Lu, 2013; Lewis, 2011). Structural couplings started playing a role only after a dominant turbine architecture had stabilized in the late 1990ies, and were constrained to the build-up of stable knowledge pipelines, e.g. through M&A and long-term technology licensing agreements between European and Chinese/Indian firms (Lema and Lema, 2012; Lewis, 2011).

Nowadays, innovative turbine designs are still predominantly developed in the few countries that were involved in early industry formation and market deployment (in particular Denmark, Germany and the USA). Territorial subsystems thus retained considerable first mover advantages through later industry life cycle phases (Huenteler et al., 2016b; Lewis, 2011; McDowall et al., 2013). This stands in contrast to the solar PV case, where various couplings at an international level made the technology pioneers from the USA and Japan lose their initial supply and market dominance over a relatively short period of time (Binz et al., 2017; Nahm and Steinfeld, 2014).

Figure 4: GIS configuration in the early wind power industry



Source: Author's own elaborations

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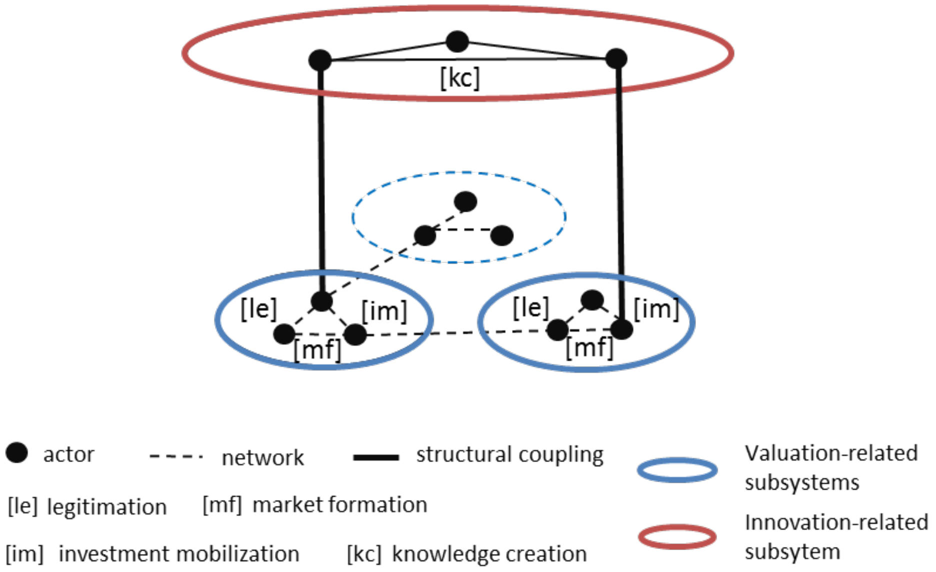
[4] A possible reading of the seminal paper by Garud and Karnoe (2003) would suggest that the Danish DUI mode won out against the STI mode predominant in the United States for gaining leadership in the wind industry.

C) Market-anchored GIS: Carbon capture and storage (CCS)(Quadrant II)

The other two examples in quadrant II and IV again vary from the two extreme cases just presented. Industries with an STI innovation mode and customized valuation system will establish GIS configurations in which knowledge-related subsystems transcend territorial boundaries, while product valuation is embedded in specific territorial contexts (see Figure 5). CCS technologies[5] are a telling illustrative example here. Technology innovation in this industry draws on basic science in STI-based knowledge fields such as geology or analytical chemistry (Markusson and Chalmers, 2013; van Alphen et al., 2010). Considerable technological progress was recently reported in this field, with significant structural couplings at an international level achieved through international research consortia and intermediaries like the International Energy Agency (IEA) or the Intergovernmental Panel on Climate Change (IPCC) (Markusson and Chalmers, 2013; Nykvist, 2013; Pickard and Foxon, 2013). Still, dynamic knowledge creation in various parts of the world are confronted with persistent (and spatially highly variegated) challenges in the valuation dimension. High-profile CCS programs in the US, the Netherlands, Norway or China all struggle with funding problems that are related to public debates about the technology's legitimacy, market prospects and other incompatibilities with the relevant regulative, normative and cognitive institutional contexts (Haarstad and Rusten, 2016; Nykvist, 2013; van Alphen et al., 2010). Even though technology proponents are continuously exploring ways to better embed CCS in specific regional contexts, pilot projects still fail in spectacular and often highly context-specific political struggles (Haarstad and Rusten, 2016).

Figure 5: GIS configuration in the carbon capture and storage industry



Source: Author's own elaborations

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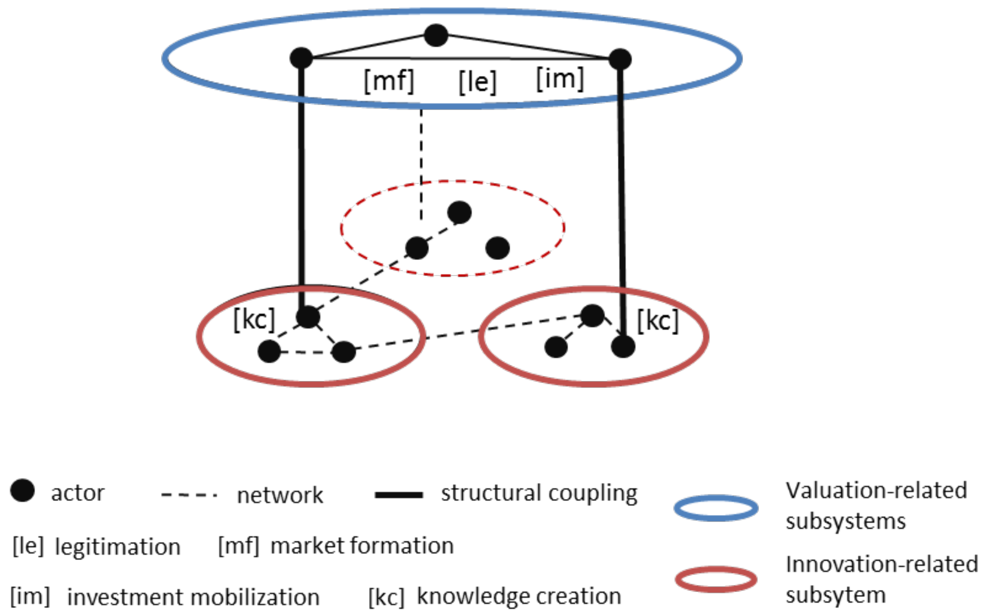
[5] Technologies to filter CO2 from the exhaust of fossil fueled power plants and store it in underground geological formations or in the ocean.

D) Production-anchored GIS: Electric cars (Quadrant IV)

Finally, the GIS type that results from DUI-based learning and standardized valuation can be characterized by the example of recent electric vehicles initiatives. It is characterized by territorially embedded subsystems at the innovation side, while new product valuation can be organized in international mass markets with standardized supply channels. The automotive industry nicely illustrates this configuration. Car manufacturers have for several decades depended on a GIS configuration in which US, European, and Asian clusters with cumulative synthetic knowledge bases in engineering, research and design played a key role in driving innovation (Dicken, 2015). At the same time, the industry's markets, distribution channels and quality criteria are strongly homogenized globally, with user tastes gravitating around a few standardized product categories (Hård and Knie, 2001). The newly emerging electric car industry still depends on this globalized valuation system, but combines it with innovative features that draw on more analytical knowledge bases (e.g. computer systems for self-driving capabilities). The increasing importance of STI-based innovation in electric vehicles may shake the historically well-aligned GIS configuration in this industry (Dicken, 2015): New entrants like Tesla or Google car use IT technology and new media applications not only to improve existing products, but also to valuate electric cars as a customizable high-tech gadget (Jeannerat and Kebir, 2016; Wesseling et al., 2015). With this introduction of analytical (and symbolic) knowledge bases, we would expect the automotive GIS to get deeply transformed over the next decades. Our framework would predict a situation in which newcomers can profit from a window of opportunity and enter STI-driven market niches that cater for user needs that are more strongly embedded in specific local institutional contexts. Even though incumbent car manufacturers are still successfully protecting the status quo, disruptive change and a deep reconfiguration of the car GIS may already be under way (Dijk et al., 2016; Truffer et al., forthcoming; Wesseling et al., 2014).

Figure 6: GIS configuration in the electric car industry



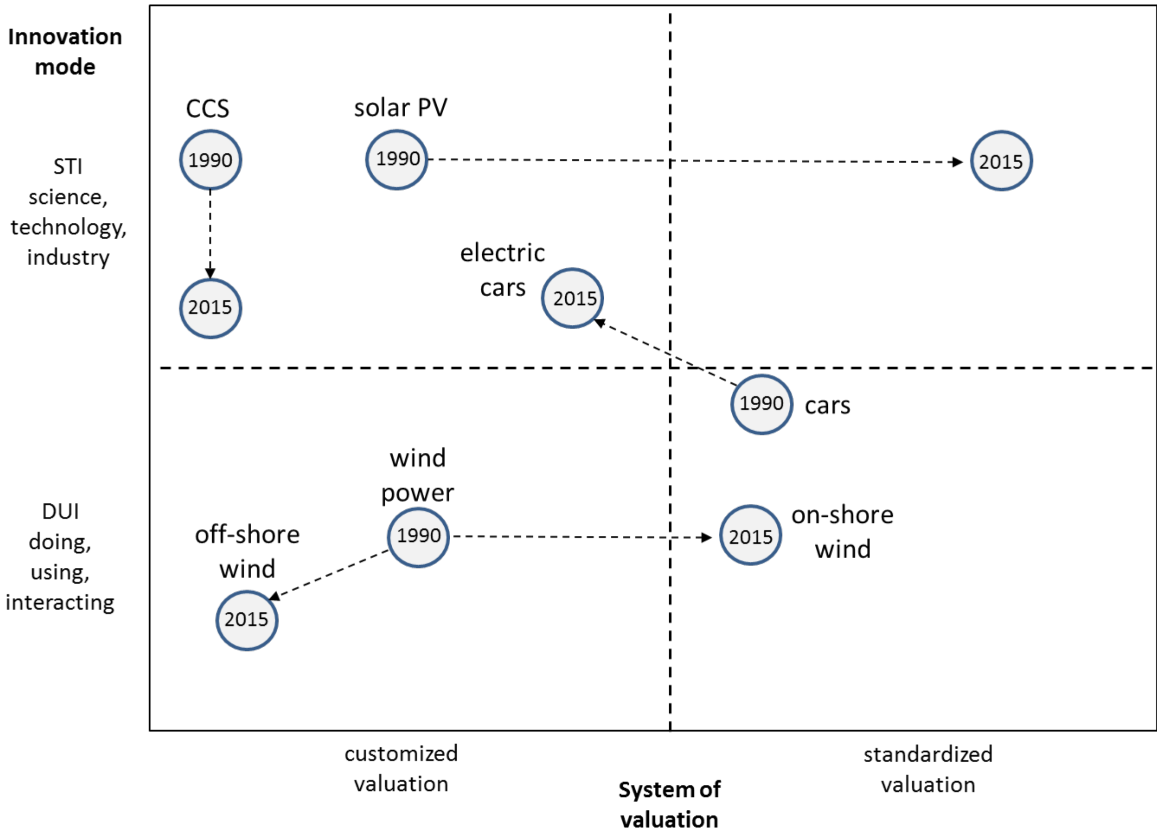
Source: Author's own elaborations

4.5 *Dynamics in GIS configuration*

The last illustrative example shows that an industry's GIS configuration cannot be expected to remain stable over time. Both the knowledge base and the valuation system may shift, e.g. when initially complex engineered products get standardized around a dominant design and develop into uniform products for global mass markets, as in the case of the solar PV industry around 2008 (Dewald and Fromhold-Eisebith, 2015; Huenteler et al., 2016a). In general, we expect customized valuation strategies to be more important in early phases of industry emergence whereas more mature products will move to increasingly standardized valuation. The solar PV and wind power GIS both showed this general pattern (cf. Figure 7); They initially emerged in institutionally embedded niche markets and gradually developed into standardized products for global mass markets. In the PV GIS, standardization is now highly advanced in both the innovation and valuation dimension (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015). In the wind case, institutional embedding still plays a key role for technological innovation in specialized market segments like off-shore wind turbines, while on-shore wind turbines are now a standardized product with price-driven global market competition. In both cases, a significant transition in the GIS's spatial configuration was thus observable after a dominant design or product architecture emerged.

Considerable shifts in GIS configurations are conceivable also in more mature industries and in the valuation dimension. An often-cited example is the Swiss luxury watch industry, where a highly standardized mass-market product got more and more attached to territorially embedded symbolic meanings (Jeannerat and Kebir, 2016). Also the recent shifts in the valuation (and innovation) dimension of the electric car industry may lead to a significant reconfiguration of its spatial GIS configuration. Relocation of innovative activity from old regions with DUI-based knowledge bases (i.e. Detroit) to regions with strengths in STI-based knowledge specialization (i.e. Silicon Valley) are already visible and likely to continue in the future. Innovation in CCS technologies, finally, has so far developed in a relative stable GIS configuration over time. While it is beyond the scope of this paper, further theorizing should assess whether and how the four GIS types can be related to distinct lifecycle dynamics and whether and when windows of opportunity for radical shifts in GIS configurations emerge in each industry type (Lee and Malerba, 2017).

Figure 7: Evolution of the GIS configuration in four clean-tech industries



Source: Author's own elaborations

5. Outlines of a research agenda, methodological challenges and policy implications

The elaborations above show that operationalizing the global innovation system framework raises novel hypotheses on how systemic innovation processes in various regions, nations, and international arenas interrelate. These feed into a research agenda with potentially highly relevant policy implications if a variety of further conceptual and methodological challenges can be resolved.

5.1 GIS – Foundations for a new research agenda

Overall, we argue that the GIS framework provides a rich meso-level heuristic for more empirically informed comparative analyses. In particular, it allows one to re-interprete the plentiful single-industry case studies from various IS traditions in a theoretically more informed, comparative perspective. For the time being we can outline a – necessarily partial and incomplete – list of promising research fields that could be informed in this realm.

First, one can explore in more depth for each GIS type how and where subsystems emerge, how subsystem formation differs between regions and what type of system resources get created where and how. Ultimately, GIS provides new perspectives on the *conditions for the emergence of positive externalities* in an innovation system. Future work would have to discern in detail how interdependencies between heterogeneous actor groups lead to externality formation at and beyond territorial boundaries and how access to the resulting system resources is organized and governed in different industries. Ideally, this work would go beyond the manufacturing industries in focus of most SIS literature (and also the examples chosen in the present contribution) and include service sectors and various creative industries (Castellacci, 2008; Martin and Moodysson, 2011). A pertinent question in this realm relates to the *GIS configurations industries with complex value chains*. I.e. the automotive, biotechnology or aerospace industries all depend on components, processes and intermediary inputs that stem from various industries with their very own innovation mode and valuation systems (Coe and Yeung, 2015). In these cases, the GIS analysis will have to be decomposed into different value chain segments and analyze how innovation dynamics unfold at the intersection of industrial and sectorial boundaries (Stephan et al., 2017).

Second, *structural coupling* as a key process in innovation system formation should be further explored. How exactly does structural coupling work, what types of actors and networks are important, and how do more informal mechanisms (i.e. at a cognitive institutional level) connect the activities in various subsystems of a GIS? One key set of research questions can be related to the *role of system builders and intermediaries* (Hughes, 1979; van Lente et al., 2003)*:* GIS need a minimum of system coordination. As discussed above, our concept emphasizes that not only transnational corporations, but also professional associations, international NGOs, city networks, international donors, consultancy firms, etc. can play an important integrative role (Fuenfschilling and Binz, 2017). Yet, how exactly they connect subsystems of a complex GIS is largely uncharted terrain. Another stream of research could be related to the *anchoring of external system resources* in specific regions and countries: How do system externalities that stem from international networks get anchored to specific local contexts and how does contextualized knowledge get up-scaled to global technology and market standards? And how does this process differ between industries? A delicate balance of external structural couplings and embedding in regional institutional contexts will be needed to connect innovation process at various spatial scales (Crevoisier and Jeannerat, 2009).

Third, an agenda that was downplayed in the above discussion relates to *issues of power*. GIS will likely not develop through harmonious cooperation, but rather be subject to permanent contestation and power struggles among interested actors (Zeller, 2000). An improved understanding should be developed on how specific actors attain a structural superior position to influence innovation beyond regional contexts. How do power asymmetries in global network architecture influence how and where novelty is developed and diffused (or not)? Connecting IS approaches more explicitly to concepts such as network governance in GPN/GVC literature (Coe and Yeung, 2015; Gereffi et al., 2005) or the regime concept from transition studies (Fuenfschilling and Binz, 2017) appears very promising here. An initial hypothesis derived from our framework is that industries which generate hard-to-control spatial spillovers (e.g. solar PV) will be less likely to develop captive value chain governance modes than industries in which territorial embedding provides early movers with sustained competitive advantages (e.g. wind power).

5.2 Methodological challenges

The multi-layered topology of GIS also implies a set of methodological challenges that were only scantly addressed in the present paper. Analyzing the activities of all actors that participate in a GIS and considering all the relevant networks and institutional contexts can quickly prove to be an overwhelming task. However, if the goal is adapting the IS concept to ongoing economic globalization, this challenge will have to be confronted (Weber and Truffer, 2017). Innovative methodological proposals have recently been formulated on how specific resource formation processes like knowledge creation (Binz et al., 2014; Stephan et al., 2017), legitimation (Markard et al., 2016), market formation (Jeannerat and Kebir, 2016; Sengers and Raven, 2015) or financial investment

(Karltorp, 2016) can be analyzed beyond pre-set spatial boundaries. At the same time, the increasing quality of global databases on patents, publications, trade statistics or pilot plant experimentation creates opportunities to define system boundaries in an empirically more informed way (Binz et al., 2014; Stephan et al., 2017; Wieczorek et al., 2015b). Finally, recent advances in social network analysis and stochastic actor-based modeling might open new inroads to empirically delimiting and analyzing GIS subsystems and their dynamic coupling patterns.

Ultimately, the choice of methodology should relate to the needs of the conceptual focus chosen and the case analyzed. The sector typology developed in section 4 might further inform system boundary setting as it provides theoretical hypotheses on the geographic configuration of GIS in various industries (Bergek et al., 2015). The GIS framework may thus provide an encompassing heuristic for positioning partial IS analysis in specific countries or regions in broader sectorial and spatial contexts. It may also enable a more causal understanding on how innovation processes in various industries develop over time and in space and on how policy making can influence the process.

5.3 Policy implications

In terms of policy implications one may ask the question what sort of new governance approaches and institutions are needed to get to grips with dynamically evolving GIS? The discussion in this paper showed that industries with a footloose GIS are most directly challenging conventional innovation policy approaches as their system resources emerge in international networks that are hard to control in any national or regional context. The experience with the national feed-in tariff for solar PV in Germany in the early 2000s illustrates this challenge. When Germany implemented an ambitious national market deployment subsidy in 2002, it aimed – among others – at creating a mass market that would provide the German PV manufacturers with a first-mover advantage (Hoppmann et al., 2014; Peters et al., 2012). Yet, given the ubiquitous international structural couplings in this GIS type, the policy did not create sustained first mover advantages for German panel manufacturers, but induced substantial spillovers to various other places, in particular to China, Korea, Taiwan or the USA (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015). The high spatial fluidity of this industry, which came as a surprise to German policy makers (Hoppmann et al., 2014), could have been explained and anticipated to some degree based on the GIS framework.

Innovation and industrial policies at a national or regional level should accordingly more closely reflect the targeted industry's GIS configuration (Binz et al., in press; Quitzow et al., 2017). According to the discussion in section 4.3, policy interventions in footloose GIS types could apply a 'free trade zone'-type policy rationale: Tax credits, low-interest loans, liberal trade policies and the creation of local centers of excellence in R&D will all support local firms to compete in fierce international price and technology competition. Industries with spatially sticky GIS, in turn could profit from policies that follow a territorially much more specific 'strategic niche management' rationale (Kemp et al., 2000): Producers, users and various intermediary actors will have to be co-located in a given place and supplied with patient capital and a (subsidized) market niche in which complex learning-by-doing and interacting can occur. In market-anchored GIS, policy interventions will more strongly depend on a 'public procurement for innovation' logic (Edquist and Zabala-Iturriagagoitia, 2012): Here, strategic (government-)funding for high-profile pilot experiments can create the spaces in which global knowledge dynamics get anchored to spatially embedded valuation dynamics. Finally, in the case of production-driven GISs, conventional RIS and cluster policies seem most adequate (Porter, 1998; Tödtling and Trippl, 2005). Policy interventions to support this industry type can focus on fostering ‘local buzz’ in dense industry-supplier-university networks, while also creating favorable conditions for international knowledge exchange (‘global pipelines’) and exports into global markets (Bathelt et al., 2004).

Last but not least, this differentiated framework may not only help to avoid unintended spatial spillovers from national policy interventions like in the solar PV case, but might also be used for identifying and eliminating system failures that inhibit the development of an innovation at an international level. The GIS framework adds a ‘global policy coordination failure’, which extends on Weber and Rohracher’s (2012) national policy coordination failure. E.g. in the solar PV case, uncoordinated national policy interventions resulted in global overcapacities and trade disputes which significantly hampered GIS actors in diffusing the innovation. Especially in footloose (and to a lesser degree in market-anchored and production-anchored GIS), international NGOs or industry associations could in principle integrate and coordinate innovation dynamics to create a common-pool global knowledge platform that is accessible to firms and policy makers around the world. Such a global governance structure would construct a more level playing fields for all involved actors (Schmidt and Huenteler, 2016) and could also be used to mitigate trade disputes and reduce overcapacities while speeding up policy learning and transition dynamics in various parts of the world. Overall, while GIS are largely emergent phenomena that cannot be actively designed or governed in a top-down manner, ample opportunities exist for future researchers to develop policy rationales that are more reflective of global interdependencies in the innovation process.

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